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THE TESTING OF PLASMA SPRAY COATINGS.(U)
MAY 76 T J ROSEBERRY, E J ONESTO, K F DUFRANE N00197-75-C-0060
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REPORT NO. MT-042

MAY 1976

THE TESTING OF PLASMA SPRAY COATINGS

A PROJECT OF THE
MANUFACTURING TECHNOLOGY PROGRAM
NAVAL SEA SYSTEMS COMMAND

FINAL REPORT

NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

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ABSTRACT

This program was conducted for the purpose of providing reference data on plasma-sprayed coatings for use in the design and repair/salvage of naval ordnance hardware. Plasma-spray deposition parameters and surface finishing techniques were developed for metal and ceramic plasma-sprayed coatings applied to mild steel, stainless steel, aluminum, brass, and K-monel. The wear characteristics of the coated shafts versus a variety of bushing materials were studied in hydraulic piston wear tests during which oil leakage rates as a function of surface finish were determined using Teflon and urethane seal materials.

As a result of the program, plasma-sprayed coatings and bushing material were identified that provided friction and wear performance at least comparable to that provided by baseline conventional cylinder materials, Teflon seals were found to provide the most reliable dynamic seal performance, and a low viscosity, polyester type resin sealer (Loctite 290) was found to be an effective sealant for both hydraulic and pneumatic applications.

The plasma-spray parameters and processing parameters and techniques developed in this program and information on the coating properties and process limitations derived from this work will be incorporated in the plasma-spray handbook being prepared for NOSL under Contract No. N-00197-73-C-0430(U).

FOREWORD

This is the final report of work completed under NAVORDSYSCOM Work Request WR-4-5995 issued to prepare reference data on the plasma sprayed coatings used in the design and repair of Naval Ordnance hardware based on functional life cycle testing. The study and testing was performed under the direction of the Naval Ordnance Station, Louisville, Kentucky through Contract Number N-00197-75-C-0060. New

This report was prepared by Battelle Columbus Laboratories and has been edited by the Naval Ordnance Station, Louisville to insure compliance and coordination with the total requirements of the NAVORDSYSCOM Work Statement.

Funding was provided by the Industrial Resources and Facilities Division (ORD-047) of Naval Ordnance Systems Command under the Manufacturing Technology Program, and was completed for the Naval Sea Systems Command (SEA-070).

Acknowledgement is given to the following persons without whose help this study would be incomplete.

Mr. T. J. Roseberry	Battelle Columbus Laboratories Columbus, Ohio 43201
Mr. E. J. Onesto	Battelle Columbus Laboratories Columbus, Ohio 43201
Mr. K. F. Dufrane	Battelle Columbus Laboratories Columbus, Ohio 43201

"This Manufacturing Technology report has been reviewed and is approved."

Thad Peake

THAD PEAKE
Director, Manufacturing
Technology Department
Naval Ordnance Station
Louisville, Kentucky

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SECTION I

INTRODUCTION

1.1 OBJECTIVES

The objective of this program was to generate reference data on plasma-sprayed coatings to be used in the design or repair/salvage of naval ordnance equipment. These data are to be incorporated into a Plasma-Spray Handbook being prepared for the Naval Ordnance Station, Louisville (NOSL) by Battelle's Columbus Laboratories (BCL) under Contract No. N00197-73-C-0430(U). The results were intended to

(a) Provide design engineers, project engineers, metallurgists, and quality assurance personnel with reliable, objective evidence to enable them to determine the most suitable materials for ordnance design or repair applications.

(b) Provide baseline assurance that the spray materials and processing procedures covered in the Plasma-Spray Handbook are compatible with naval ordnance repair and salvage requirements.

1.2 BACKGROUND

The Plasma-Spray Handbook is intended to provide engineering and production personnel with a thorough understanding of the plasma-spray process, including processing parameters and techniques, coating properties, and process limitations. The handbook is to be used as a guide for the selection of a coating material for specific NOSL repair applications. It is being prepared on the basis of past experience and established technology. However, since many of the material combinations and potential plasma-spray coatings for NOSL ordnance equipment are unusual in terms of industrial applications, a functional test program using these materials was felt to be necessary to develop the needed data for the handbook.

Although the Plasma-Spray Handbook is intended to be a guide for all NOSL repair and salvage operations, the scope of the functional testing program could not realistically include all of the sliding geometries, speeds, loads, temperatures, lubricants, and atmospheres to be encountered in the various mechanisms. Therefore, hydraulic cylinders were chosen as a typical and important application for plasma-spray coatings. Since wear is an extremely complicated phenomenon, direct extension of the resulting data to other mechanisms must understandably use appropriate care*. For example, changes in humidity have been reported to change the wear of brass

* E. Rabinowicz, Friction and Wear of Materials, John Wiley and Sons, Inc., New York, 1965.

by a factor of 100, while changes in environment, such as from air to oil, can have an even greater effect*. The most important factor in extending the data to other applications is insuring that the same wear mechanism is operative. On a practical basis, this usually requires that the important variables of contact pressure, speed, temperature, geometry, and lubrication do not vary widely from the test conditions.

With the recognition of the inherent limitations of the general applicability of the functional test data obtained from hydraulic cylinders, the efforts were considered to be only a necessary beginning in supplying needed data where none now exists. If extension of the data to unique wear problems in various mechanisms results in unsatisfactory performance, specific tests would be required to identify the appropriate plasma-spray coating. Such tests, coupled with field experience in rebuilding NOSL ordnance equipment according to the Plasma-Spray Handbook procedures, will provide the ultimate guide for selection of plasma-spray materials.

1.3 TECHNICAL APPROACH

1.3.1 Functional Testing

All functional evaluations were conducted using commercial double-ended hydraulic cylinders with modified end bushings, seals, and rods. The cylinders had a 1.5-inch bore, 1-inch cylinder rod, and a 12-inch stroke. Side loads were applied to the end bushings via the cylinder rod by dead weight loading. A mineral oil hydraulic fluid, MIL-SPEC No. MIL-F-17111, supplied by NOSL was used for all testing. Each end of the double-ended cylinder had the same physical conditions (base rod material, coating, cylinder bushing material, side loading, etc.).

The coated cylinder rods were cycled continuously at a rate of 40 cycles per minute for a total in excess of 20,000 cycles or until excessive leakage occurred or significant damage to the coated rod or bushing was observed. The system was operated against a hydraulic back pressure of 2000 psig.

1.3.2 Substrate and Bushing Materials

The operating conditions were established using the commercial cylinder rod and bushing material. The performance data obtained with the commercial cylinders were used as the basis of comparison for alternate bushing materials and cylinder rod materials coated by plasma spraying. The following is a list of the materials evaluated, all of which are from the material matrix in the Plasma-Spray Handbook.

---

* E. F. Finkin, "What Happens When Parts Wear", Machine Design, March 19, 1970, pp 148-154.

Cylinder Bushing Material

Cylinder Rod	Steel (1020)	K-Monel (Monel 500)	Aluminum-Bronze	Stainless Steel (Type 316)	Aluminum (6061)
Steel	X	X	X	X	X
K-monel	X	--	--	--	--
Aluminum Bronze	X	--	X	X	--
St. steel	X	--	X	X	X
Aluminum	X	--	--	X	X

X designates combination evaluation
-- designates no evaluation.

1.3.3 Selection of Coating, Impregnating, and Finishing Parameters

Coating materials were selected primarily on the basis of their abrasion and corrosion resistance. In plasma spraying these materials, effort was made initially to use plasma-spray parameters (power levels, powder feed rates, spray distance) as close as possible to those recommended by the material supplier or specific plasma-torch manufacturer. Those parameters were then modified as necessary to obtain optimum coating properties (density, coating integrity, uniformity, and freedom from surface cracks).

All plasma-sprayed coatings applied in this program were impregnated with pore-filling sealant, cured, and finish ground to obtain an impervious, smooth-finished surface. Impregnating materials were evaluated on the bases of compatibility with the hydraulic fluid used, ease of application, sealing ability, and effect on friction and wear properties.

1.3.4 Rod-Bushing Material Compatibility

Compatibility and wear characteristics of selected spray materials with the 5 substrate materials of the material matrix were evaluated. Cylinder rods of these materials sprayed with various coating materials were wear tested against bushings of these materials. The degree of bushing and/or coating wear was observed and coefficients of friction for each of the tested combinations were calculated.

1.3.5 Seal Testing

Two seal materials, Teflon and Urethane, were evaluated against coated cylinder rods. The specific types of seals used were: Teflon Flange Seals, supplied by Miller Fluid Power Corp., Bensenville, Ill. and Urethane

Seal Compound 9250, supplied by Disogrin Industries Corp., Manchester, New Hampshire. Both static and dynamic observations of seal performance were made. Data were obtained on seal efficiency as a function of surface finish for both materials.

Only this type of seal (a flanged, lip seal) was evaluated as it was felt that O-ring seals were not suitable for this application and time did not permit an evaluation of chevron-type seals.

SECTION II

WORK PERFORMED

2.1 TEST SPECIMENS

Test specimens consisted of pairs of cylinder rods fabricated from each of the five selected substrate materials. Each set (pair) of rods was plasma spray coated with one of the candidate wear-resistant materials, and the coating impregnated with a pore-filling sealer and finish ground. The fabrication of the test specimens, selection of coating materials, and plasma spray, sealing, and finishing procedures are described in the following sections.

2.1.1 Fabrication

The cylinder rods used as substrates for the coatings evaluated in this work were fabricated at BCL's machine shop facility. They were patterned after the standard cylinder rods used in the Miller Model DH50R double acting hydraulic cylinder. The configuration and dimensions of the respective halves of each pair are shown in Figures 1a and b. As fabricated, the diameter of the shafts was left oversize and a thirteen-inch section of the mid-portion of each was undercut to a depth of 0.015 inch to accept the plasma-sprayed coating. When surface finishing the coating, the diameter of the shafts was ground to the specified dimension (1.000 $^{+.000}_{-.001}$ inch).

2.1.2 Coating Material Selection

Candidate coating materials for protection were chosen on the basis of their physical, mechanical, and chemical properties (abrasion resistance, hardness, corrosion resistance, etc.). Effort was made not to use "proprietary" wear-resistant compositions, but rather to use materials commonly available from more than one supplier. Two metals, molybdenum and nickel-chrome, and two oxides, an Al_2O_3-TiO_2 blend and Cr_2O_3, were used in this work. Powder specifications are listed in Table 1.

2.1.3 Sample Preparation

Prior to plasma spraying, the shafts were thoroughly degreased and cleaned using trichloroethylene and ethyl alcohol (200 p). The cleaned shafts were grit blasted using a 60/40 aluminum oxide grit, then coated with a .002 to .003 inch bonding layer of nickel-aluminum.

2.1.4 Plasma Spraying

Plasma spray was conducted for the most part using a Metco, Inc. Type 3MB plasma-spray torch, as this is the same type of equipment used at NOSL. The torch was mounted on an automated tooling rig to provide a constant, reproducible traverse rate at a constant torch-to-workpiece distance.

TABLE 1. PLASMA-SPRAY POWDER SPECIFICATIONS

Material	Description	Supplier	Particle Size
Aluminum oxide - titanium oxide composite, Al_2O_3-TiO_2 (Metco 130)	87% Al_2O_3 13% TiO_2	Metco, Incorporated Westbury, Long Island, N.Y.	-270 mesh + 15μ (-53 + 15μ
Chromium oxide, Cr_2O_3 (Metco 106 NS)	99% Cr_2O_3	Metco, Incorporated	-140 mesh + 10μ (-106 + 10 μ)
(AVCO PP-39)	98% Cr_2O_3	Bay State Abrasives, Westboro, Mass.	-325 mesh + 10μ (-44 + 10μ)
(Plasmadyne 309F)	97% Cr_2O_3	Plasmadyne, Santa Ana, Cal.	-325 mesh (-44μ)
Molybdenum, Mo (Metco 63 NS)	99% Mo	Metco, Incorporated	-200 mesh + 30μ (-75 + 30μ)
Nickel-chrome alloy, Nichrome (Metco 43C)	80% Ni 20% Cr	Metco, Incorporated	-140 + 325 mesh (-106 + 45μ)
Nickel-aluminum composite Nickel aluminide (Metco 450)	4.5% Al 95.5% Ni	Metco, Incorporated	-170 + 325 mesh (-90 + 45μ)

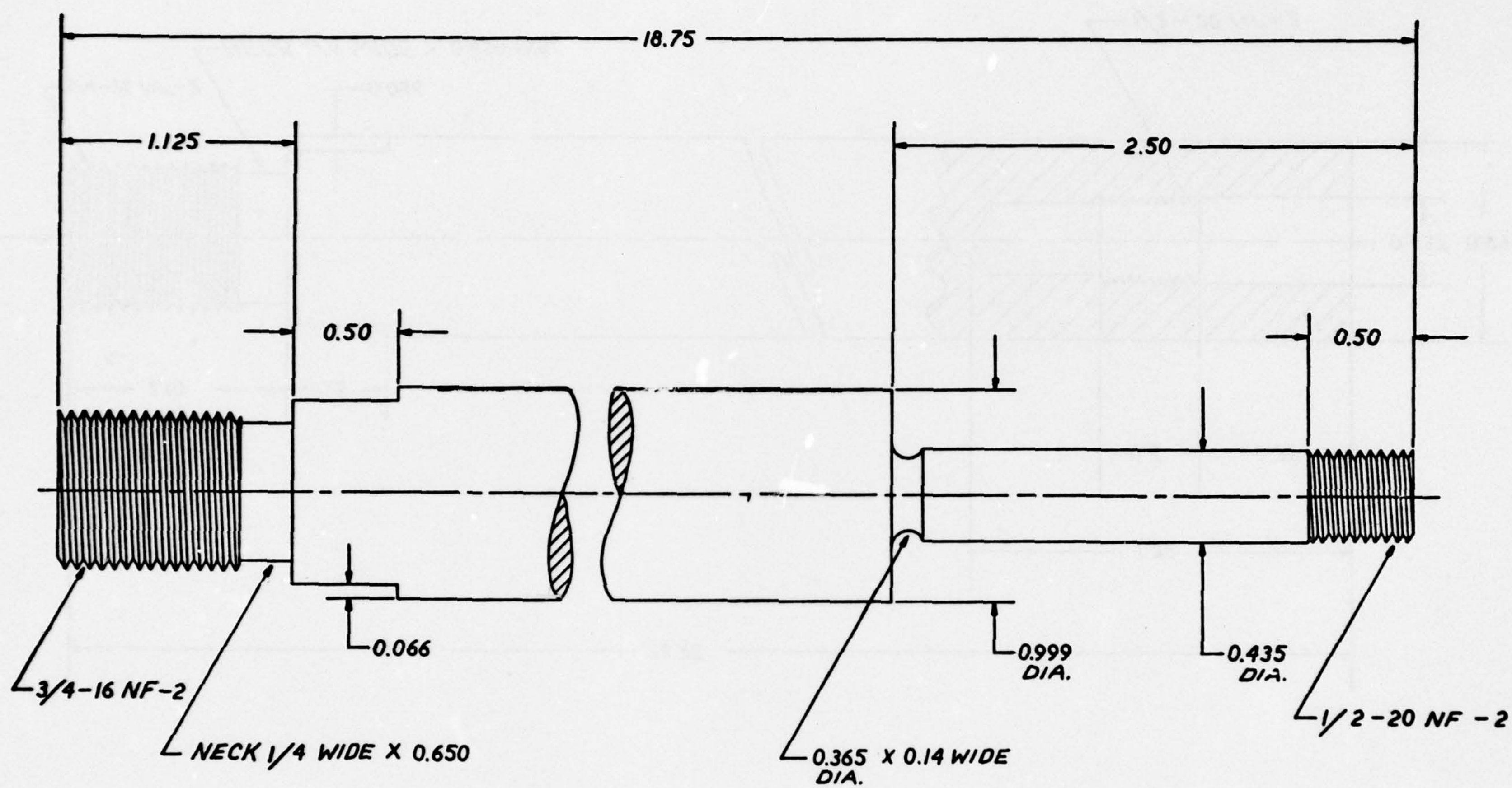


FIGURE 1a. HYDRAULIC CYLINDER ROD - MALE

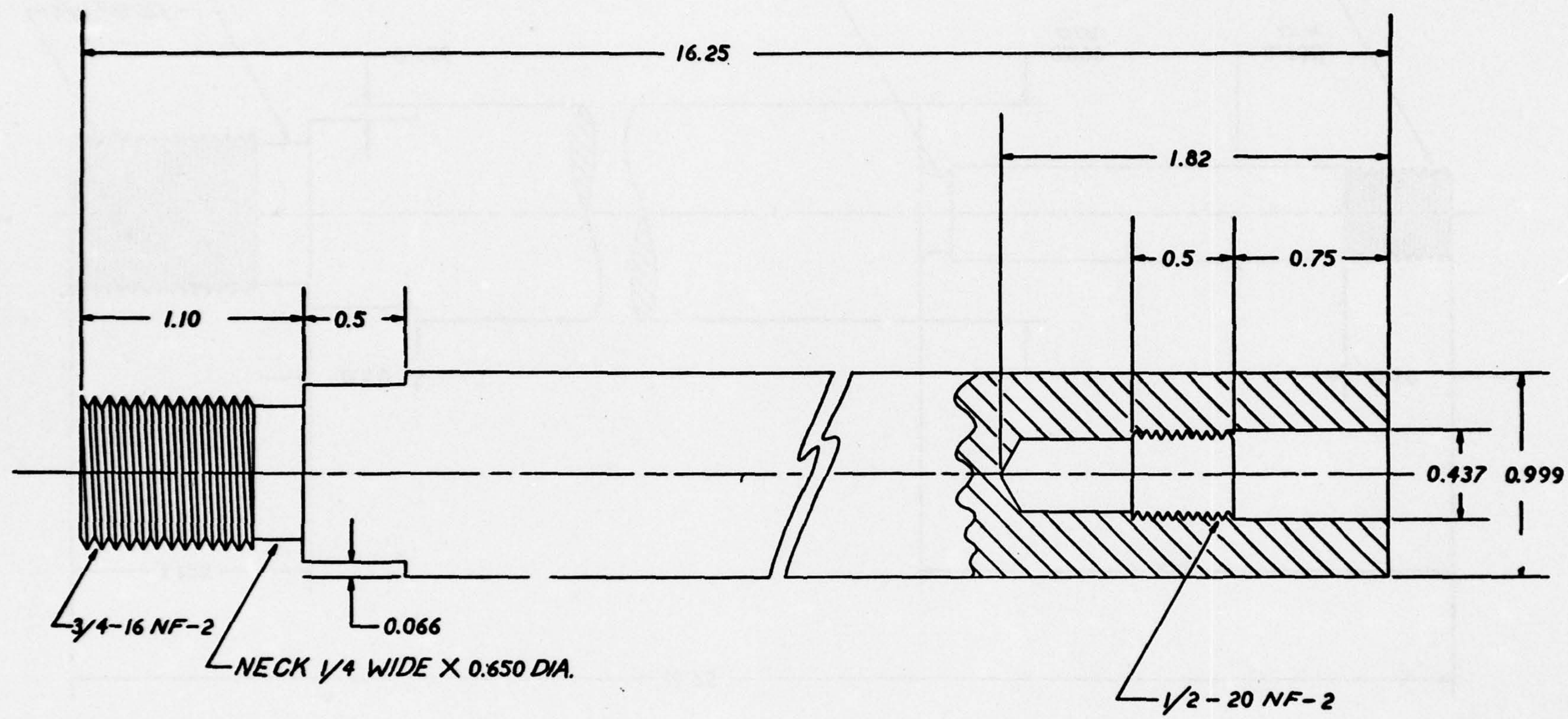


FIGURE 1b. HYDRAULIC CYLINDER ROD - FEMALE

The plasma-spray parameters for each of the coating materials and for the subcoat materials are found in Appendix A. Separate sets of parameter sheets are included for coatings sprayed at BCL and those sprayed by NOSL personnel under BCL supervision.

2.1.5 Sealing

Prior to surface finishing, each set of coated rods was impregnated with a pore-filling sealer material to prevent infiltration of the plasma-sprayed coatings by air or hydraulic fluid. Two types of sealer were evaluated initially. These were Metco Type BP, a clear, synthetic phenolic, and Loctite 290, a low-viscosity, single-component, polyester-type resin. In later tests, a third sealant, Epon 828 epoxy, was used to reseal surface porosity which was produced during finish grinding. This is discussed in a later section of this report. To apply the phenolic sealer, the coated rods were immersed in a 3-inch diameter by 24-inch container of sealant, sufficient sealant being added to cover the coatings, and the container with the rods was placed in a pressure vessel. The vessel was pressurized with compressed air to 250 psi for five minutes. Upon removal, the impregnated shafts were placed in an oven at 350 F for one hour to cure the sealer.

The polyester-type resin sealant was applied to the coated shafts by brushing it on as the shafts were rotated in a lathe. Being a thin, low-viscosity liquid, the sealant was readily drawn by capillary action into open porosity where it hardened by an anaerobic process. Coated rods were thoroughly wet with sealant, which was allowed to harden, then post-cured by heating to 250 F for 30 minutes.

Based both on performance and on ease of application, the polyester-resin sealant, Loctite 290, was selected for use on the coated rods subjected to functional testing. Visual observation of finished, impregnated surfaces indicated better penetration of the coating and static pressure tests confirmed these observations. Specifically, when pressurized with hydraulic oil in the bench test apparatus shown in Figure 2, the phenolic impregnated shafts permitted infiltration of oil through the coating at pressures as low as 20 psi. On the contrary, polyester-resin impregnated shafts did not leak when pressurized in this apparatus to 100 psi. In later tests, all coated shafts were shown to withstand 2000 psi pressure when they were assembled into the hydraulic wear-test apparatus and allowed to stand under pressure overnight.

Representative coated shafts were subsequently subjected to even greater pressures. The bench-testing apparatus was modified as shown in Figure 3 to determine the effectiveness of sealed coatings against air infiltration. Randomly selected coated shafts representing each of the coating materials were assembled in the apparatus, pressurized with air to 300 psi and held at pressure for 5 minutes. The coated surface protruding above the pressurized cylinder was doused with SNOOP leak detection liquid [Mil Spec. MIL-L-25567C (ASG) Type 1] and observed. No air leakage was observed in any of the coated rods tested. These shafts were then assembled in a standard hydraulic cylinder and pressurized to 3500 psi with the hydraulic fluid used in the functional wear tests. This pressure was maintained for 15 minutes, during which time no infiltration of fluid through the sealed coatings was observed.

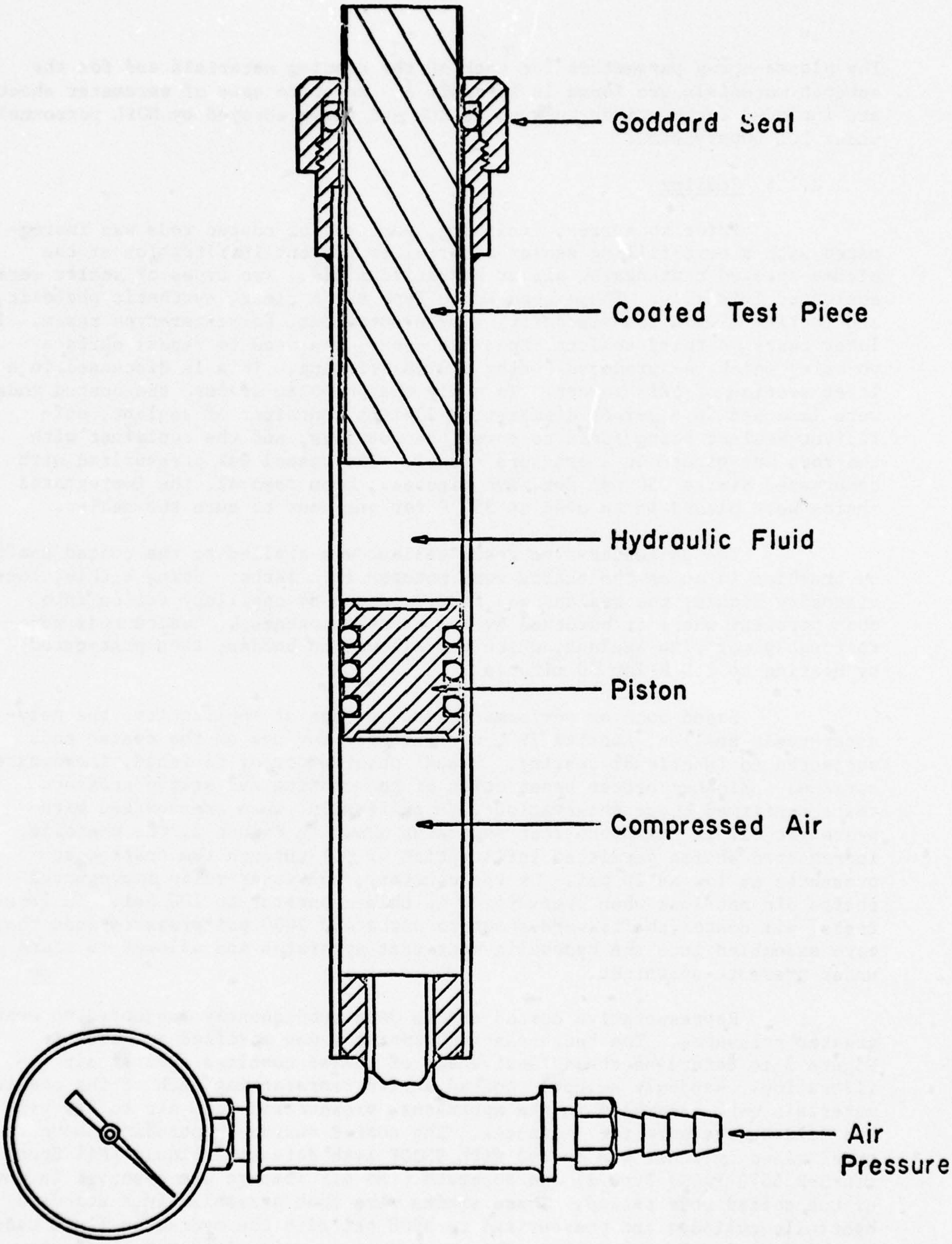


FIGURE 2. PRESSURE-TESTING APPARATUS

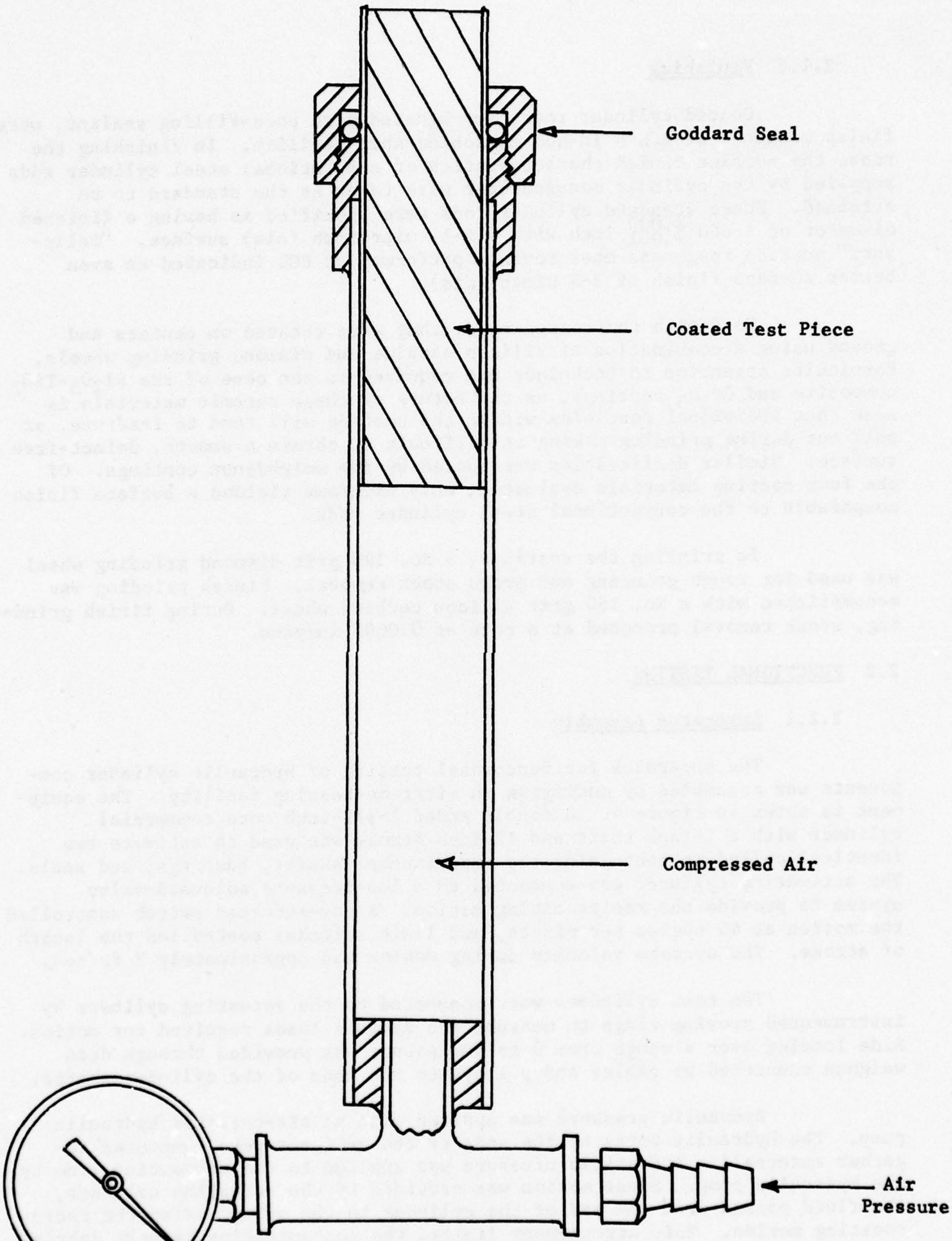


FIGURE 3. AIR PRESSURE TESTING APPARATUS

2.1.6 Finishing

Coated cylinder rods, impregnated with pore-filling sealant, were finish machined at BCL's in-house machine shop facility. In finishing the rods, the surface finish characteristics of conventional steel cylinder rods supplied by the cylinder manufacturer were taken as the standard to be attained. These standard cylinder rods were specified as having a finished diameter of 1.000 $^{+.000}_{-.001}$ inch with a 5-10 microinch (cla) surface. "Tallysurf" surface roughness measurements performed at BCL indicated an even better surface finish of 2-3 μinch (cla).

To finish the coated rods, they were rotated on centers and ground using a combination of silicon carbide and diamond grinding wheels. Particular attention to technique was required in the case of the Al_2O_3-TiO_2 composite and Cr_2O_3 coatings, as the nature of these ceramic materials is such that individual particles within the coating will tend to fracture, or pull out during grinding making it difficult to obtain a smooth, defect-free surface. Similar difficulties were posed by the molybdenum coatings. Of the four coating materials evaluated, only nichrome yielded a surface finish comparable to the conventional steel cylinder rods.

In grinding the coatings, a No. 120 grit diamond grinding wheel was used for rough grinding and gross stock removal. Finish grinding was accomplished with a No. 180 grit silicon carbide wheel. During finish grinding, stock removal proceeded at a rate of 0.0005 in/pass.

2.2 FUNCTIONAL TESTING

2.2.1 Apparatus Assembly

The apparatus for functional testing of hydraulic cylinder components was assembled by modifying an airframe-bearing facility. The equipment is shown in Figure 4. A double ended 1-1/2-inch bore commercial cylinder with a 1-inch shaft and 12-inch stroke was used to activate two identical cylinders containing the experimental shafts, bushings, and seals. The activating cylinder was connected to a low-pressure solenoid-valve system to provide the reciprocating motion. A cam-actuated switch controlled the motion at 40 cycles per minute, and limit switches controlled the length of stroke. The average velocity during motion was approximately 2 ft/sec.

The test cylinders were connected to the actuating cylinder by instrumented proving rings to measure the dynamic loads required for motion. Side loading over a range from 0 to 300 pounds was provided through dead weights connected by cables and pulleys to the ends of the cylinder shafts.

Hydraulic pressure was applied with an air-operated hydraulic pump. The hydraulic ports at the ends of the cylinder were connected together externally, and static pressure was applied to the connecting line by the hydraulic pump. Since motion was provided by the actuating cylinder, the fluid passed from one end of the cylinder to the other during the reciprocating motion. This arrangement limited the contamination by wear debris to the cylinder in which it was produced. A static pressure of 2000 psig

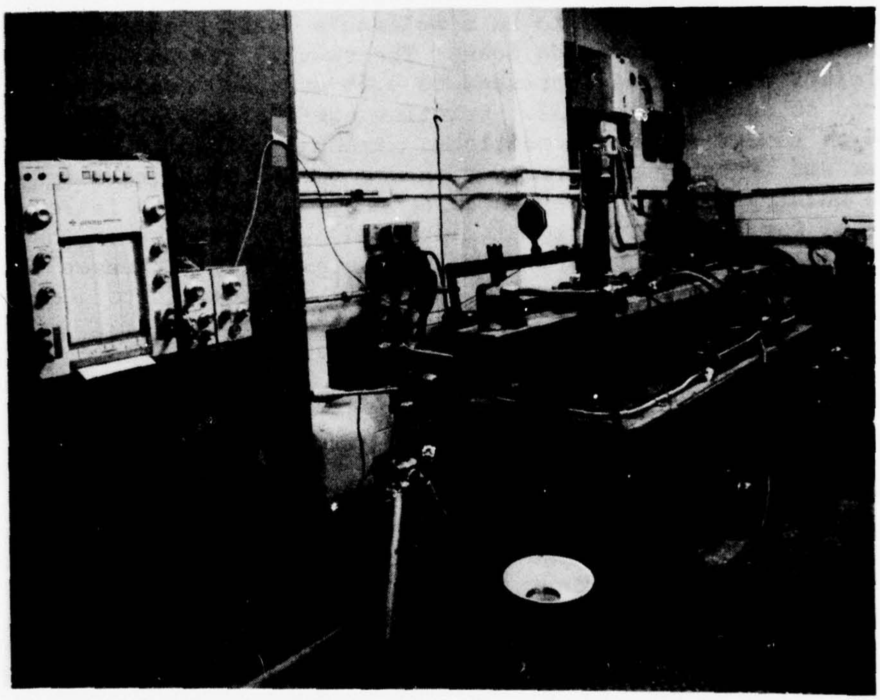


FIGURE 4. HYDRAULIC CYLINDER-TESTING APPARATUS

with MIL-F-17111 hydraulic fluid was used in all experiments.

2.2.2 Establishing Operating Conditions

The operating conditions for the experiments were established using two unaltered commercial cylinders. Tolerable side loads were studied in an experiment in which the side loads were increased incrementally to determine the effect on coefficient of friction. The results are presented in Table 2. The cylinder was operated at each side load for approximately 500 cycles to allow the system to equilibrate. The maximum side load was limited to 200 pounds, which is extremely high for the relatively long 1-inch shafts used on the cylinders. The coefficient of friction increased with increasing load to a maximum of 0.25. There was no indication of galling or severe sliding conditions during the experiment.

Since a 100-pound side load resulted in a coefficient of friction near the maximum and appeared to be a tolerable load, a longer run was made with a continuous 100-pound side load. The results are summarized in Table 3. The coefficient of friction increased to 0.66 at 5,000 cycles, after which it continued to decrease to 0.32. Friction coefficients at these levels are indicative of severe sliding conditions. Axial scoring was noticeable early in the test and probably occurred during the period of highest friction. Although the bushing contact pressure based on projected area is low (approximately 50 psi for a 100-pound total side load), the bending of the relatively long shafts leads to high edge-loading stresses. These stresses were probably responsible for the scoring and would be expected to decrease as wear reduces the contact stress by increasing the contact area. The shaft wear was limited to the scored areas and was not measurable with a micrometer. The bushing wear was limited to poorly defined areas near the edge and was less than 0.0001 inch in depth.

With the excessive coefficients of friction resulting with a 100-pound side load, a second new cylinder was run with a 50-pound side load (25 pounds on each end) to measure changes in coefficient of friction and the seal leakage. The results are shown in Figure 5. The coefficient of friction dropped rapidly in the first 5,000 cycles and reached a plateau of approximately 0.06 for the remainder of the run. A value of 0.06 is low for boundary lubricated sliding contacts and indicates very mild sliding conditions. The end leakage remained fairly constant throughout the run. Since the cylinder supplier considered a 50-pound total side load to be excessive for this size cylinder, a 30 ml leakage in 20,000 cycles with a 50-pound side load was assumed to be the baseline for further experiments on modified cylinders.

Before disassembly, the side load was increased in increments to determine whether excessive friction could be induced. The results are presented in Table 4. No excessive values were recorded, and the coefficient decreased after running for 2400 cycles except for the run with a 200-pound load. This indicates that higher side loads can be tolerated on a cylinder if the loads are increased in steps after running at lower loads for extended cycles. For example, much higher values of friction and leakage were recorded during the run in which a 100-pound load was applied from the start.

TABLE 2. STUDY OF TOLERABLE SIDE LOADS ON STANDARD HYDRAULIC CYLINDER

Side Load (Shared by 2 ends), lb	Driving Force, lb	Friction Force, lb	Coefficient of Friction
0	23.1	0	--
40	27.5	4.4	0.11
80	40.2	17.1	0.21
100	46.9	23.8	0.24
150	60.3	37.2	0.25
200	73.8	50.7	0.25

TABLE 3. PERFORMANCE OF STANDARD HYDRAULIC CYLINDER WITH A CONSTANT 100-POUND SIDE LOAD

Cycles	Driving Force, lb	Friction Force, lb	Coefficient of Friction
26	49.2	26.1	0.26
967	51.4	28.3	0.28
5,057	89.4	66.1	0.66
12,067	63.8	40.7	0.41
18,347	59.5	36.4	0.36
20,069	55.3	32.2	0.32

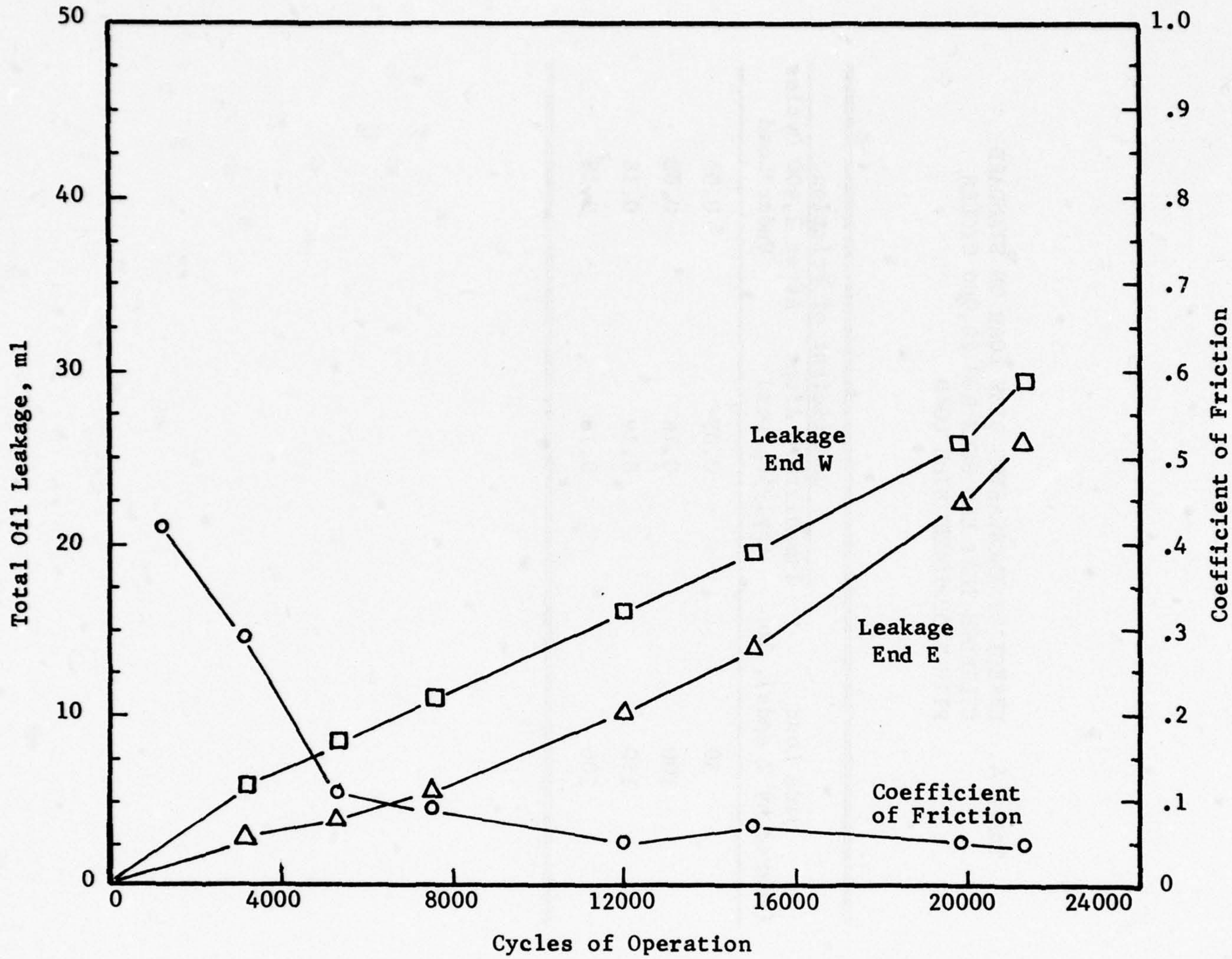


FIGURE 5. PERFORMANCE OF STANDARD HYDRAULIC CYLINDER WITH 50-POUND SIDE LOAD AND 2,000 PSIG STATIC HYDRAULIC PRESSURE

TABLE 4. EFFECT OF INCREASING SIDE LOAD ON STANDARD CYLINDER THAT HAD BEEN RUN 20,000 CYCLES WITH A 50-POUND SIDE LOAD

Side Load (shared by 2 ends), lb	Coefficient of Friction: Immediately After Applying Load	Coefficient of Friction: After 2,400 Cycles Under Load
50	0.07	0.05
100	0.16	0.08
150	0.19	0.16
200	0.16	0.18

Wear measurements made on the shafts after running showed the wear to be very localized. The general surface wear was less than the depth of the original finishing scratches, or approximately 2 microinches. The obvious shaft wear occurred in longitudinal scored lines running the length of the contact area. The maximum depth measured was 60 microinches, and the typical depth was only 20 microinches. Typical areas on the shaft before and after testing are shown in Figure 6. The original grinding scratches were still present over much of the surface between the longitudinal scored areas. The wear of the bushings was confined to very small areas near the edges and measured less than 0.0001 inch in depth.

2.2.3 Standard Operating Condition

From the results of the experiments on standard (unmodified) hydraulic cylinders, the following conditions were established for the tests on plasma-sprayed shafts and alternate bushing and seal materials.

1. 2000 psig static hydraulic pressure throughout the run.

2. Operation at 40 cycles per minute to 20,000 cycles or failure, whichever occurred first. The sliding speed was approximately 1.3 ft/sec

3. 50-pound total dead-weight side load (25 pounds on each end), which produced a projected-area contact pressure of approximately 25 psi

4. Continuous monitoring of coefficient of friction

5. Continuous collection and measurement of end leakage

6. Before-and-after measurements of bushing and shaft wear

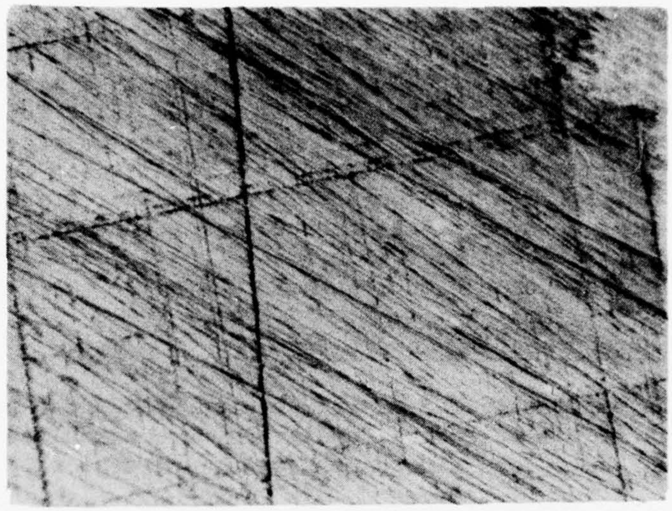
Also, from the results on the tests with standard cylinders, the following were used as the basis for comparison of the performance of the plasma-sprayed cylinder rods and alternate bushing materials. Acceptable performance was taken to be

1. Seal leakage of 30 ml or less.

2. Bushing wear of 0.0001 inch or less

3. General cylinder rod (shaft) wear to be restricted to less than the depth of the finishing scratches or 2 microinches, whichever is less. Concentrated cylinder rod wear to be restricted to longitudinal scratches measuring 60 microinches or less in depth

Use of the results obtained with the conventional cylinder as the baseline of comparison for the performance of the various plasma-sprayed coatings and bushing materials was decided upon for the following reasons.



100X

(a)

New shaft surface

100X

(b)

Worn shaft surface

FIGURE 6. WEAR ON STEEL SHAFT OF CONVENTIONAL HYDRAULIC CYLINDER AFTER 20,000 CYCLES WITH 50-POUND SIDE LOAD AND 2,000 PSIG HYDRAULIC PRESSURE

1. Most of the cylinder-rod and cylinder-bushing materials combinations in the material matrix (without plasma-spray coatings) are completely unacceptable for boundary-lubricated sliding contact, as determined from general engineering practice. Therefore, if all of the uncoated materials could not be examined, the choice of material combination for the baseline becomes arbitrary.

2. The conventional sintered-iron bushing material and steel cylinder rod proved to perform very well and, thereby, formed a rigorous baseline of comparison for alternate bushing materials and plasma-spray coatings.

3. With the complexities of wear, the usefulness of any data developed would be in terms of comparing one material relative to another under the same conditions, as opposed to a quantitative evaluation of the absolute performance.

4. Once coated, the properties of the base material do not enter into the wear process occurring at the coating surface. Therefore, the results obtained evaluate the performance of the coating, and the wear properties of the underlying base material are inconsequential. The base material would enter into the wear process only if it negatively influences the bond with the coating, i.e., the bond is poor and the coating flakes off.

2.3 SALT CORROSION TESTS

Ten coated shafts, representing each of the coating material-substrate combinations were subjected to salt fog exposure as per ASTM test method B117-73. In this test, the samples were exposed to an atomized 5% salt (NaCl) solution at a temperature of 95 F for a period of 100 hours. Upon removal from the fog chamber, the shafts were rinsed, to remove salt residue, and dried.

Examination of the coated shafts after exposure revealed no apparent damage to the coatings as a result of exposure to the corrosive salt atmosphere. However, with the exception of the stainless steel and K-monel shafts, the exposed metal ends, including screw threads on all the other specimens were badly pitted and corroded (Figure 7). The extent of this corrosion was such that the shafts could not be reassembled and properly aligned in the hydraulic cylinders to be wear tested.

Based on careful examination of both the metal and ceramic coatings it would appear that little, if any, difference in wear performance would be found even if functional testing could be performed. There was no evidence of peeling, blistering, or delamination of any of the coatings either metal or ceramic. Closer examination showed the surfaces to be smooth and unpitted. Based on these observations, the conclusion is drawn that the wear performance of the shafts after salt spray exposure would be unchanged.

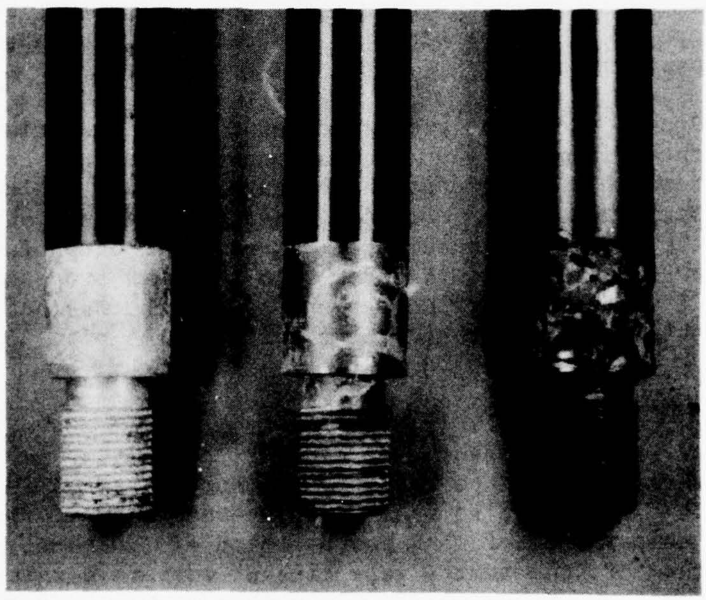


FIGURE 7. COATED SHAFTS FOLLOWING SALT SPRAY EXPOSURE

SECTION III

RESULTS AND DISCUSSION

3.1 GENERAL OBSERVATIONS

All of the results of the cylinder-wear experiments are summarized in Table 5. Since all combinations of seal type, filler material, surface finish, shafts material, coating, and bushing material were not run, the specific cause of wide variations in performance cannot be identified in all cases.

Typical results of leakage and coefficient of friction throughout an experiment are presented in Figures 8 and 9. The coefficient of friction and operating force given in Table 5 were taken from the last 2,000 cycles of operation where an equilibrium condition was usually reached. The coefficient of friction between the shaft and bushing was calculated from the difference in operating force with and without the 50-pound side load. Since the type of measurement cannot account for changes due to misalignment or seal interaction, the measurement is not rigorous and must be used only as an indication of relative shaft-bushing friction. Observation on the various results are presented below.

3.2 RAM-BUSHING MATERIAL CAPABILITY

3.2.1 Bushing Materials

Of the various bushing materials, the aluminum bushings and the 316 Cres. bushings in contact with metal coatings showed the highest wear. The aluminum bushings had the highest total volume removed through wear because the wear was fairly uniform along the length of the bore. In contrast, the other bushings had the wear confined to the edges where shaft bending resulted in the highest edge loadings. Since the sliding behavior of aluminum and 316 Cres. is typically poor, the results with the cylinders are consistent with general engineering practices.

No relationship was established between bushing material and shaft wear. The most severe shaft wear was in the form of longitudinal scratches. The depth of the scratches was typically 20 to 60 microinches, and overall shaft wear was less than 0.0001 inch in all cases. Therefore, all of the bushing materials appear to be satisfactory in terms of minimizing shaft wear.

3.2.2 Coating Materials

Of the four coating materials evaluated, only the molybdenum showed different and undesirable performance. Cylinders run with molybdenum-coated shafts had the highest operating forces and tended to maintain a high coefficient of friction throughout the 20,000 cycle experiments. The only

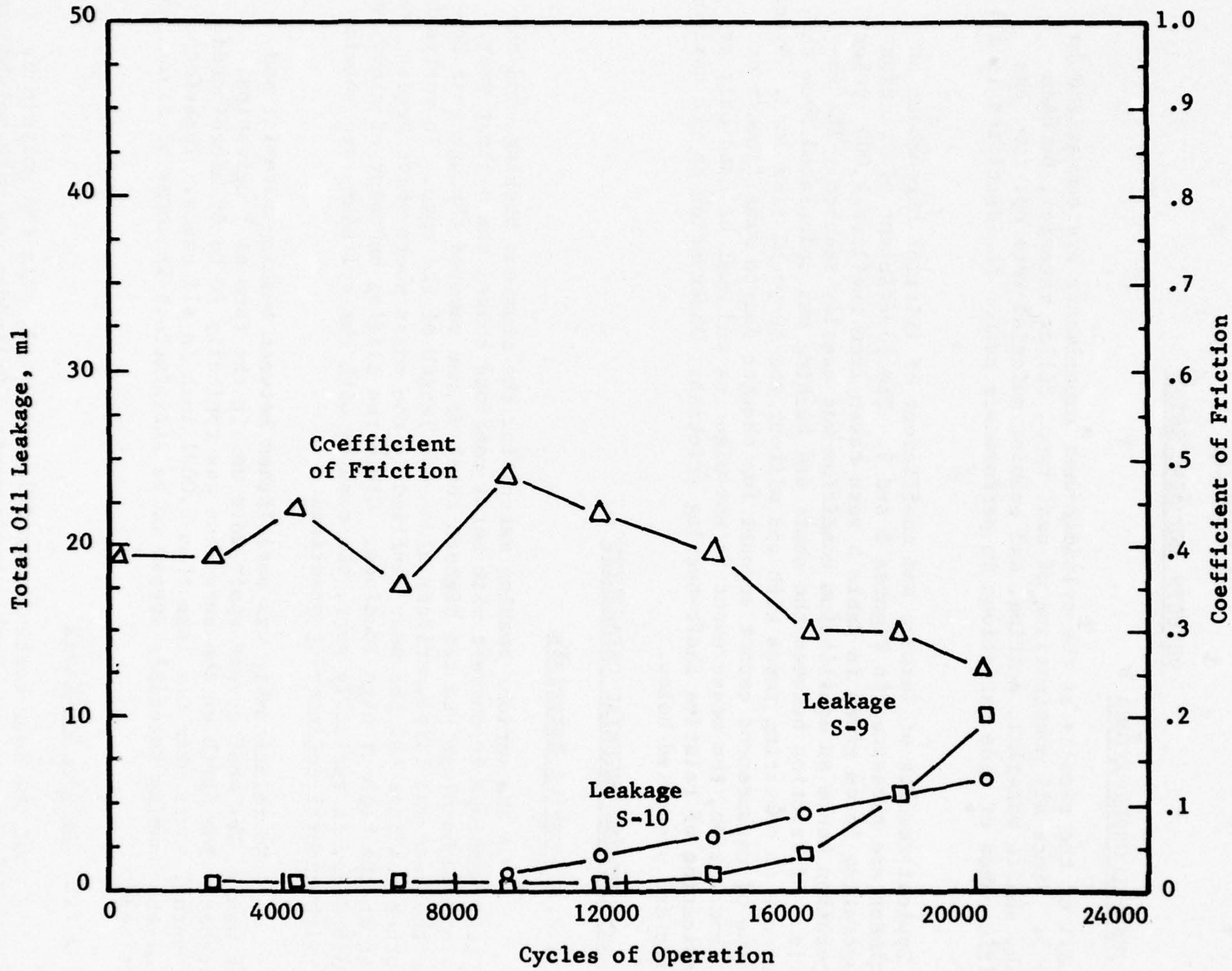


FIGURE 8. PERFORMANCE OF HYDRAULIC CYLINDER WITH STEEL SHAFTS PLASMA SPRAYED WITH MOLYBDENUM AND ALUMINUM-BRONZE END BUSHINGS (Conventional Seals, 50 Pound Total Side Load and 2,000 Psig Static Hydraulic Pressure)

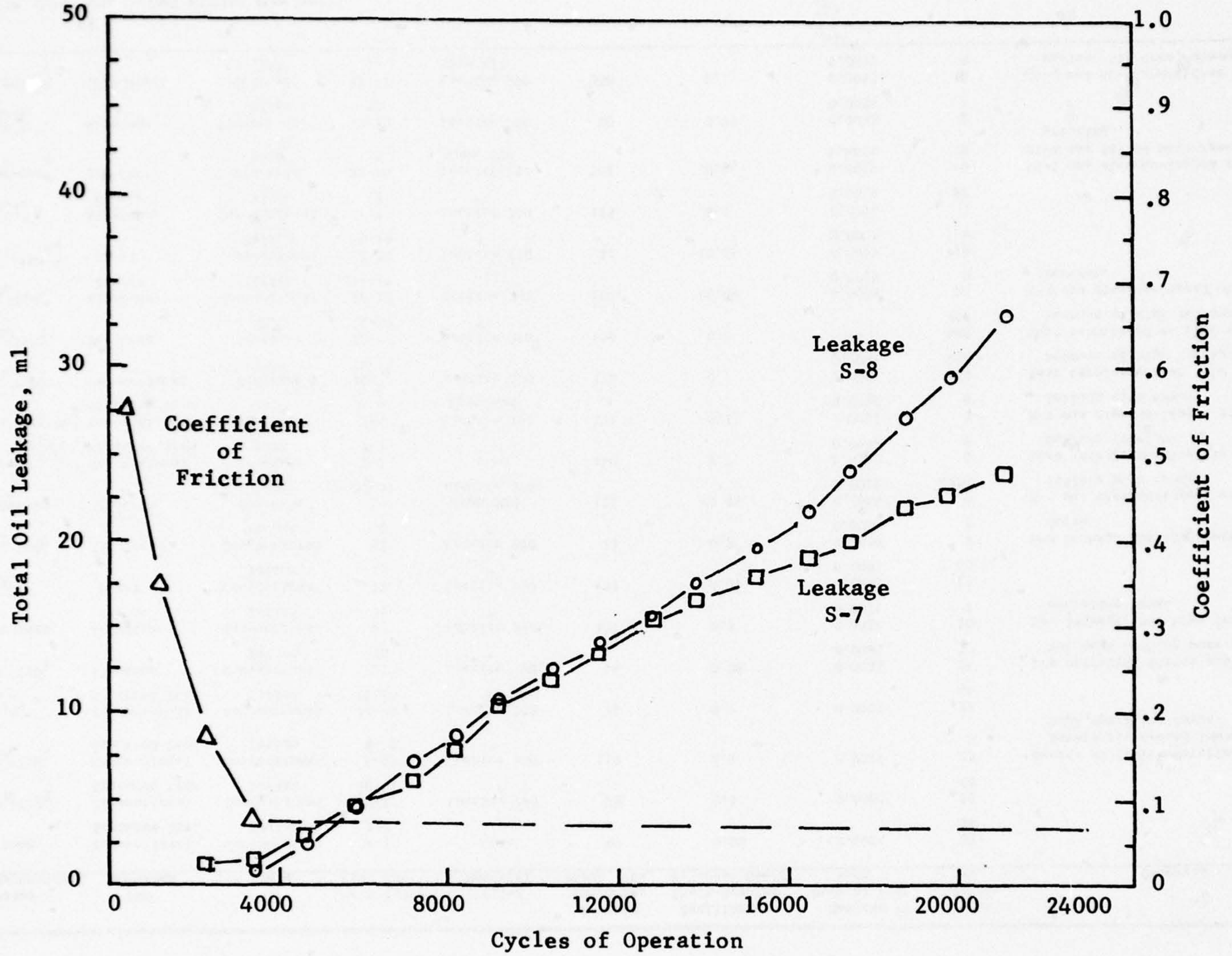


FIGURE 9. PERFORMANCE OF HYDRAULIC CYLINDER WITH STEEL SHAFTS PLASMA SPRAYED WITH Al_2O_3-TiO_2 AND ALUMINUM END BUSHINGS (Conventional Seals, 50 Pound Total Side Load, and 2,000 Psig Static Hydraulic Pressure)

TABLE 5. RESULTS OF HYDRAULIC CYLINDER EXPERIMENTS WITH 50-POUND TOTAL SIDE LOAD, 2000 PSIG STATIC HYDRAULIC PRESSURE AND 20,000 CYCLES OF OPERATION

Shaft		Plasma Spray Coating	End Bushings	Seals	Shaft Finish, μin. cla	Filler Material	Average Operating Force, lbs.	Equilibrium Shaft-Bushing Friction Coeff.	Maximum ** Bushing Wear, inch	Total Leakage, ml	Comments
Conventional Steel		none	Conventional Sintered Iron	Conventional Teflon	2-3	none	49	0.06	<0.0001	29	
					2-3					26	
Steel	S-1	Al_2O_3-TiO_2	Conventional Sintered Iron	Conventional Teflon	10-27	Loctite 290	85	0.3	0.0005	80	
	S-2	"			10-11	"				35	
Steel	S-3	Al_2O_3-TiO_2	Conventional Sintered Iron	Conventional Teflon	8-13	Loctite 290	119	0.2	0.0008	25	Excess of filler material apparently caused low leakage and high operating force.
	S-4	"			8-15	"				5	
Steel	S-5	Cr_2O_3*	Conventional Sintered Iron	Conventional Teflon	13-28	Loctite 290	78	0.2	0.0005	22	
	S-6	" *			12-25	"				44	
Steel	S-7	Al_2O_3-TiO_2	Aluminum	Conventional Teflon	21	Loctite 290	44	0.08	0.0033	24	Low operating forces and friction but high bushing wear.
	S-8	"			20	"			0.0081	33	
Steel	S-9	Molybdenum	Aluminum-Bronze	Conventional Teflon	45	Loctite 290	137	0.3	0.0011	10	Low leakage, but high friction and operating force.
	S-10	"			52	"			0.0031	7	
Steel	S-5	Cr_2O_3	Monel	Conventional Teflon	22	Loctite 290	103	0.09	0.0001	17	
	S-6	"			15	"			0.0007	43	
Steel	S-3	Al_2O_3-TiO_2	316 Cres.	Conventional Teflon	12	Loctite 290	73	0.2	0.0000	3	Low leakage and low operating force.
	S-4	"			8	"			0.0009	8	
Steel	S-9	Molybdenum	316 Cres	Urethane 9250	30	Epon 828	121	<0.08	0.0044	0	S-9 was diamond-lapped prior to filling with epoxy.
	S-10	"			32-57	Loctite 290			0.0019	1350	
Conventional Steel		none	Conventional Sintered Iron	Urethane 9250	2-3	none	144	0.7	0.0000	0	Zero leakage resulted in high shaft-bushing friction.
		"			2-3				0.0006	0	
K-Monel	M-1	Nickel-Chrome*	Conventional Sintered Iron	Urethane 9250	2-4	Loctite 290	172	0.7	0.0003	0	M-2 was diamond-lapped prior to filling with epoxy.
	M-2	" *			4	Epon 828			0.0000	0	
Brass	B-1	Al_2O_3-TiO_2	Conventional	Urethane 9250	10-17	Loctite 290	172	0.7	0.0011	800	Test termination at 5600 cycles because of high leakage.
	B-2	"			14-19	"			0.0001	400	
Brass	B-1	Al_2O_3-TiO_2	316 Cres.	Urethane 9250	10-17	Loctite 290	150	0.2	--	690	Test terminated at 3700 cycles because of high leakage.
	B-2	"			14-19	"				700	
Brass	B-1	Al_2O_3-TiO_2	Aluminum-Bronze	Conventional Teflon	10-17	Loctite 290	107	<0.08	0.0008	21	B-2 was diamond-lapped prior to running.
	B-2	"			14-19				0.0019	0	
Brass	B-3	Al_2O_3-TiO_3*	Monel	Conventional Teflon	8-10	Loctite 290	81	<0.08	0.0017	26	
	B-4	" *			8-10	"			0.0025	6	
316	SS-2	Cr_2O_3*	Aluminum-Bronze	Conventional Teflon	18	Loctite 290	105	0.1	0.0026	3	
	SS-3	" *			31	"			0.0019	27	
316	SS-1	Molybdenum*	316 Cres.	Urethane 9250	28-60	Loctite 290	302	0.4	0.0019	0	SS-1 was diamond-lapped after grinding SS-4 was filled with Epoxy 828 after grinding.
	SS-4	" *			13	Epon 828			0.0071	0	
316	SS-2	Cr_2O_3*	Aluminum	Conventional Teflon	13-19	Loctite 290	80	0.09	0.0033	2	
	SS-3	" *			22	"			0.0054	7	
316	SS-1	Molybdenum*	1020 Steel	Urethane 9250	32-47	Loctite 290	300	0.7	0.0035	0	SS-1 and SS-4 unmodified from run against 316 Cres. above
	SS-4	" *			16	Epon 828			0.0035	0	

* Sprayed at NOSL.

** Shaft wear limited to minor longitudinal scoring (see text).

TABLE 5. (CONTINUED)

Shaft		Plasma Spray Coating	End Bushings	Seals	Shaft Finish, in. cla	Filler Material	Average Operating Force, lbs.	Equilibrium Shaft-Bushing Friction Coeff.	Maximum** Bushing Wear, inch	Total Leakage, ml	Comments
Aluminum	A-1	$Al_2O_3-TiO_2$	316 Cres.	Conventional	11	Loctite 290	67	<0.08	0.0001	24	
	A-2	"		Teflon	14	"			0.0004	31	
Aluminum	A-1	$Al_2O_3-TiO_2$	Conventional	Urethane	13	Loctite 290	81	<0.08	0.0001	400	Test terminated at 8800 cycles because of high seal wear and leakage.
	A-2	"	Sintered Iron	9250	11	"			0.0000	700	
Aluminum	A-1	$Al_2O_3-TiO_2$	Aluminum	Urethane	10	Loctite 290	239	0.4	0.0035	700	Test terminated at 3700 cycles because of high seal wear and leakage.
	A-2	"		9250	13	"			0.0032	60	
Aluminum	A-5	$Al_2O_3-TiO_2$*	1020 Steel	Urethane	6	Loctite 290	200	<0.08	0.0020	1460	A-6 was diamond-lapped prior to running.
	A-6	"*		9250	6	"			0.0012	22	

* Sprayed at NOSL.

** Shaft wear limited to minor longitudinal scoring (see text).

experiment with a nickel-chrome coating also had a relatively high operating force and high coefficient of friction, but the excellent surface finish produced with this coating resulted in low leakage.

The two oxide coatings generally showed similar performance. Differences in results could usually be related to other parameters such as finish or seal material rather than to the coating itself. Both of these coatings are extremely wear resistant, but are also subject to impact damage because of their brittle nature. For example, shaft B-4 (NOSL-coated Cr_2O_3 on brass) was chipped at the center by impacting lightly with a hammer after the 20,000-cycle run. Further running for 1,100 cycles resulted in a 9 ml additional leakage, compared with only 6 ml leakage for the entire 20,000 cycles. Shafts coated with these materials will require careful handling during finishing, installation, and operation to prevent impact damage and resulting seal deterioration.

3.2.3 Shaft Materials

No performance differences could be attributed to the type of shaft material. The lower modulus of elasticity with the aluminum and brass shafts was clearly evident in the amount of side deflection during direction reversals on each cycle. There were no instances of performance problems caused by poor bonding between the coatings and shaft materials. If the coatings remain intact, the sliding performance would be expected to be controlled by the coating properties rather than the shaft material, which was confirmed in the experiments.

3.3 INFLUENCE OF SHAFT SEALING AND FINISHING PARAMETERS ON SEAL PERFORMANCE

3.3.1 Seal Materials

The two seal materials studied in the cylinder wear experiments were the conventional Teflon lip seals normally used in the test cylinders and urethane 9250 seals, which are of the same compound and design as the seals currently being used by NOSL in field applications. The two materials showed widely different performance. The Teflon seals were associated with low cylinder operating forces, insensitivity to shaft surface finish, and constant low leakage. In contrast, the urethane seals resulted in high cylinder operating forces, strong sensitivity to shaft surface finish, and zero leakage under compatible shaft conditions. If the shaft surface was not filled or finished properly, the urethane seals suffered gross wear and associated high leakage.

With the cylinder design incorporating a bushing outboard of the seal, lubrication of the bushing is provided by oil drawn through the seal by the shaft. When the leakage is restricted to zero by a very effective seal, the bushing runs unlubricated and experiences associated high friction with the shaft. Therefore, a slight leakage is desirable in this cylinder design. The urethane seals proved to be extremely conforming on a microscale since zero leakage was recorded on shafts with a surface roughness as high as 60 microinches cla. This is probably a result of their soft nature

compared to the Teflon seals. The relatively hard Teflon seals probably do not remove the oil from the shaft surface pores, which results in the constant leakage experienced. These results indicate that the urethane seals should be used in applications where very low leakage is desirable and bushings do not depend on leakage for lubrication. The Teflon seals are preferred for applications requiring leakage for lubrication and those requiring low operating forces.

3.3.2 Effect of Surface Finish

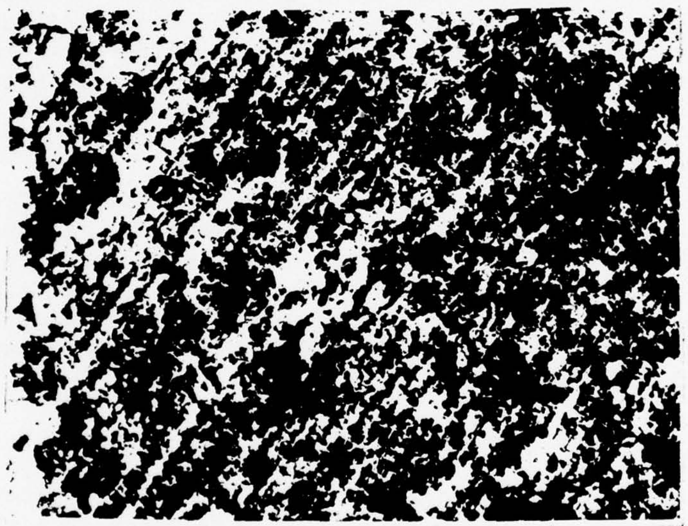
Since the plasma-spray process inherently produces some porosity, which influences the final surface finish, the effect of shaft surface finish on performance is an important variable to evaluate. A typical surface area after grinding is shown in Figure 10. Shaft surface finishes were obtained in the study from 2 to 60 microinches cla with different materials and finishing techniques. However, the results show clearly that the surface finish in terms of cla roughness is far less important than is the method of final finishing.

The Teflon seals were found to be insensitive to shaft roughness and finishing technique in most cases. For example, molybdenum-coated shaft S-10 with a surface finish of 52 microinches leaked only 7 ml in 20,000 cycles, compared with 30 ml leakage with the conventional steel shaft finished to 3 microinches cla. In runs with the oxide coatings having a finish of 8 to 30 microinches cla, the Teflon seals leaked amounts comparable to the standard cylinder.

In contrast, urethane 9250 seals run against the Loctite-290 filled as-ground shafts were completely destroyed by wear in as few as 4,000 cycles. Such gross seal wear on as-ground shafts was eliminated only if the surface roughness was 4 microinches cla or less, such as with shaft M-1. Shaft A-5, with a 6 microinch cla finish on Cr_2O_3, caused the urethane seal to wear and leak excessively.

Experiments on the effect of surface finish on urethane 9250 seal performance showed that high surface roughness could be tolerated providing the surface was filled with epoxy after grinding or was lapped after grinding. For example, urethane seals run against molybdenum-coated shafts SS-1 and SS-4 showed no leakage after 20,000 cycles. Shaft SS-1 was lapped after grinding and shaft SS-4 was filled with epoxy after grinding. Combining lapping and filling with epoxy was also successful, as shown by molybdenum-coated shaft S-9 run with a urethane seal without leakage. Identical shaft S-10 run without treatment after grinding leaked 1350 ml in 20,000 cycles. Lapping also decreased the leakage with a Teflon seal, as shown by shaft B-2 compared with B-1. No leakage was measured with shaft B-2, which had been lapped after grinding. This was the only shaft run with a Teflon seal that did not leak.

To further establish these observations, a series of shafts which had been previously wear tested was lapped and retested against urethane and against Teflon seals. The shafts tested and the results obtained are listed in Table 6. In nearly every case, the lapping effected a reduction in



100X

FIGURE 10. TYPICAL Al_2O_3-TiO_2 SPRAYED SURFACE AFTER GRINDING

TABLE 6. STUDY OF EFFECTS OF DIAMOND LAPPING

Shaft		Coating Material	Seals	Average Operating Force-16	Equilibrium Coefficient of Friction	Total Leakage-ml	Previous Results: Average Operatng Force-16	Previous Results: Equilibrium Coefficient of Friction	Previous Results: Total Leakage -ml
Aluminum	A1	Al_2O_3-TiO_2	Teflon	88	0.055	0.1	67	0.08	24
	A2					2.3			31
Aluminum	A1	Al_2O_3-TiO_2	Urethane	150	0.15	Very high	81	0.08	400
	A2					" "			700
Brass	B1	Al_2O_3-TiO_2	Teflon	119	0.57	19.1	107*	<0.08*	21*
	B2					2.7			0*
Brass	B1	Al_2O_3-TiO_2	Urethane	150	0.31	2.9	172	0.7	800
	B2					Very high			400
Steel	S5	Cr_2O_3	Teflon	136	0.31	0	78	0.2	22
	S6					0			44
Steel	S5	Cr_2O_3	Urethane	177	0.11	8.1	-- None available--		--
	S6					17.4			
Steel	S7	Al_2O_3-TiO_2	Teflon	75	0.14	2.3	44**	0.08**	24**
	S8					0.4			33**
Steel	S7	Al_2O_3-TiO_2	Urethane	176	0.35	Very high	--None available --		--
	S8					0			

* Previously tested against Al-bronze bushing.
** Previously tested against aluminum bushing.
All others tested against conventional sinered iron bushings.

leakage between the rod and the seal. However, this reduced leakage was usually accompanied by an increased operating force and slightly higher coefficient of friction due to the decreased lubrication.

The lapping procedure consisted of 1/2 hour of lapping with diamond abrasive on a soft cloth supported by a wood backing. The shaft was supported and turned in a lathe at slow speed. No change in surface roughness was measured by the lapping. The benefit obtained was apparently in breaking the corners and edges of the surface porosity in the coating and in removing any areas protruding from the surface on a microscale. In effect, the procedure removed the cutting edges that were abrading the urethane seal material. The same effect was obtained by filling the surface porosity with epoxy and thereby preventing the soft, conforming urethane from entering the pores.

3.3.3 Effect of Filler Material

All of the shafts were filled with Loctite 290 after spraying but prior to grinding. After grinding, there was no evidence of the filler in the surface porosity. Either it had not penetrated to the depths of the finished surface or it was removed by the grinding operation. Since the shafts exhibited no intra-coating leakage in bench tests or when assembled and pressurized in the functional test apparatus, the latter must be assumed.

Structurally, a thermal-sprayed coating contains some interconnecting pores and some totally closed pores. The interconnecting pores, which can produce pathways through a coating, will be filled when the coating is impregnated by a sealant. The closed pores, being isolated, will not. Apparently, during grinding, many of these closed pores are laid open, thereby giving rise to a layer of unfilled surface pores on the finished shaft.

Metallographic examination of a cross-section of a coated rod impregnated with Loctite 290 sealer was inconclusive in determining depth of sealant penetration. It was not possible to distinguish the virtually colorless sealant material in the coating matrix. What was observed, though, was a greater number of closed rather than interconnecting pores. The fact remains, however, that the coatings did not leak.

Improved surface filling was obtained with Epon 828 epoxy applied after grinding to final dimensions. The epoxy was vacuum impregnated by coating the surface placing the shaft in a vacuum, scraping the excess epoxy off with a shaft seal, and rotating the shaft while curing at 150 F in an oven for 4 hours. The shafts were run directly without further surface treatment. Microscopic examination before and after running showed the presence of epoxy in the porosity. The surface of epoxy in the pore areas was abraded by wear, but the bulk of the epoxy filler was clearly intact.

3.3.4 Static Seal Performance

After assembly of the hydraulic cylinders for testing, a 2,000 psi static hydraulic pressure was applied overnight prior to running. In no

case was any leakage measured from the static exposure. Apparently, the porosity was not interconnected across the seal width or the Loctite 290 had penetrated sufficiently to close the subsurface pores. This result indicates that static leakage should not be a problem with the seal configurations used in the program.

SECTION IV

SUMMARY AND CONCLUSIONS

4.1 MATERIAL COMBINATIONS

Plasma-sprayed coatings and bushing materials were identified that provided friction and wear performance at least comparable to that provided by the baseline conventional cylinder materials. Similar performance can be expected by use of these combinations in hydraulic cylinders of similar design and mode of operation. A summary of the friction and wear performance is presented in Table 7. Application of the combinations listed as "Recommended" in Table 7 to other sliding situations must be made with caution for the following reasons.

1. The results were obtained from complete hydraulic cylinders, which prevents a rigorous measurement of friction and wear because of the possible influences of misalignment and variations in geometry from component to component in the various cylinders.

2. Wear performance is strongly influenced by the presence of lubricants. The tests were all conducted using MIL-F-17111 hydraulic fluid as the lubricant. The use of an alternate lubricant may alter the performance of the various combinations, while operation with no lubricant would probably invalidate the results completely.

3. The extension of any wear data from one sliding application to another is valid only if the same wear mechanism is maintained. Dramatic performance differences are experienced when the combination of sliding speed, contact pressure, atmosphere, and temperature result in operation in a different wear regime.

Other conclusions based on the friction and wear results, with the section of this report in which they are discussed indicated in parenthesis, are as follows:

1. The wear of the plasma-sprayed coatings was negligible in all cases, which is similar to the results obtained with the conventional steel shafts (3.2.1).

2. The two ceramic plasma-sprayed coatings resulted in superior friction and wear performance compared with the two metallic coatings (3.2.2).

3. Bonding between the plasma-sprayed coatings and the various shaft materials was satisfactory; no instances of blistering or peeling were observed (3.2.3).

TABLE 7. PERFORMANCE SUMMARY OF CYLINDER ROD COATINGS AND BUSHING MATERIALS FOR USE IN HYDRAULIC CYLINDERS

Cylinder Rod Coating	Sintered Iron (Conventional)	Steel (1020)	K-Monel (Monel 500)	Aluminum Bronze	Stainless Steel (Type 316)	Aluminum (6061)
Al_2O_3-TiO_2	A	C	C	A	A	B2
Cr_2O_3	A	A	A	B2	C	B2
Nichrome	B1	C	C	C	C	C
Molybdenum	C	B1,2	C	B1,2	B1,2	C

Key: A - Recommended combination
B - Not recommended because (1) high friction, and/or (2) high bushing wear
C - Not evaluated.

4. While the ceramic coatings are extremely wear resistant, their inherent brittleness requires caution in handling and service to prevent chipping from impacts (3.2.2).

5. The various shaft materials produced no differences in overall performance.(3.2.3).

6. Aluminum and stainless steel bushings experience high wear rates and appear unacceptable in a cylinder-bushing application (3.2.1).

7. The plasma-sprayed coatings were unaffected by the ASTM salt-fog test (2.3).

4.2 SEAL AND FILLER PERFORMANCE

The following conclusions were drawn from the results regarding the performance of shaft seals and organic fillers to seal the porosity in the plasma-sprayed coatings.

1. The most reliable dynamic seal performance was obtained with Teflon seals. The seals resulted in low-friction operation, low seal wear rates, uniform (but low) leakage to lubricate the outboard end bushings, and insensitivity to shaft surface finish (3.3.1 and 3.3.2).

2. The urethane shaft seals were found to produce widely varying cylinder performance. When the shaft surface finish was compatible with the seals, the seal wear was low, the leakage was zero, and the shaft-bushing friction was high from lack of lubrication. When the surface finish was incompatible, the seal wore rapidly, and the leakage was catastrophic. Therefore, the use of these seals must be limited to applications where a controlled leakage is not required to lubricate components of the mechanism (3.3.1).

3. The compatibility of shaft surface finish with urethane seals does not correlate with surface roughness as measured by rms or cla, per se. The various finishes (either high or low roughness) could be made compatible either by lapping to break the sharp edges of the porosity or by filling the near-surface porosity with epoxy after finishing (3.3.2).

4. Loctite 290 sealer, a low-viscosity, single-component, polyester-type resin which penetrated open porosity by means of capillary action, acts as an effective sealant in both hydraulic oil and air applications. Surface porosity observed after grinding is apparently due to the exposure of totally closed pores, which no sealant will penetrate. A post-finishing treatment with a surface sealant, such as Epon 828 epoxy provides an improved surface (3.3.3).

4.3 RECOMMENDED FURTHER EFFORTS

The results obtained from the hydraulic cylinder functional testing confirm that plasma-sprayed coatings can be used to repair and salvage naval ordnance equipment that has worn beyond usable limits. However, because of necessary limitations in the efforts, the results of the program leave several important areas unexplored. Data must be obtained in these areas before the choice of materials to repair specific components can be made on a routine shop basis. Selected, critical experiments should be designed to produce the needed information.

The most important factor in designing wear-related tests is a recognition that wear is not an inherent material property. Therefore, in all cases of wear-related studies, efforts should be made to reduce the test design so that only the component wear phenomenon in question is studied. The resulting test will be more simple, thus permitting a larger number of tests to be accomplished, while providing basic data useful for life predictions. However, in all cases, the tests must reproduce the operative wear mechanism to be valid. This can be accomplished only by closely simulating the actual sliding conditions in terms of speed, contact pressure, atmosphere (including lubrication), temperature, and mating materials. These parameters can be varied over ranges of interest in the tests to determine the degree of permissible extension to other similar sliding situations.

Specific areas requiring further testing include:

1. Use of conventional bearing metals to rebuild worn bearing surfaces. Previous BCL experiments conducted for the Naval Air Systems Command on airframe bearings have shown plasma-sprayed aluminum bronze bearings to have higher load capacity and improved wear resistance compared with wrought versions of the alloy. Similar experiments should be conducted on specific components from ordnance hardware. Metallic coatings would combine improved machinability with ductility to resist impact damage, as compared with ceramic coatings.

2. Measurement of wear rate to permit life predictions. Because of the complicating factors of edge loading and misalignment in the hydraulic cylinder tests, no meaningful wear rate data were attained. Tests are needed, using simple geometries that reproduce the actual sliding conditions, to develop wear rate data. The test parameters should be varied over the entire service range experienced in actual hardware to determine transition points in the wear mechanism from mild to severe wear.

3. Maximum capacity in concentrated load contacts. Wear surfaces having concentrated contact loading, such as cams, gears, and guide surfaces for rolling followers require data on maximum allowable contact pressure. Since the subsurface stresses generated by such contacts will be applied to the bond between the base metal and coating, an experimental determination must be made of the critical stress to cause destruction of the bond. Important variables include the elastic properties of the coating and substrate, thickness of the coating, and the properties of any bond improvement coating used.

4. Maximum allowable impact loading. Mechanism components that degrade by a combination of sliding wear and impact, such as locks, stops, or guide surfaces, require data relating maximum allowable impact loading to prevent destruction of the plasma-sprayed coating. Similar to the concentrated load contacts, the mechanical properties of both the coating and substrate are important, as well as the bond strength.

5. Corrosion resistance of coatings. While the two ceramic and two metallic coatings studied displayed excellent corrosion resistance, other metallic coatings required for specific components may be subject to corrosion. Comparison tests should be made to rate the corrosion resistance of potential coating materials to the base materials they are replacing. The effect of organic fillers also should be studied in this regard.

APPENDIX

PLASMA-SPRAY PARAMETER SHEETS FOR BCL-SPRAYED SHAFTS AND NOSL-SPRAYED SHAFTS

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PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS plasma

SPRAYING SCHEDULE NO.

SPRAY IN ACCORDANCE WITH SPEC. NO.

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME BCL

SIGNATURE

DATE 2/11/75

PREPARATION

Method of Cleaning 200 P alcohol
Masking Information
Grit Metcolite
Grit Type and Size 60/40 Grit Blast psi 60
Nozzle to Work Distance 4 - 6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. 3M7A-GH
Nozzle (Cathode) Type No. 3M11A
Type of Gas Used (1) Argon
Type of Gas Used (2) Hydrogen
Nozzle Orifice Size .250

ARC GAS SETTINGS

Regulator (1) psi 100 ± 2
Regulator (2) psi 50 ± 2
Console psi 100/50 ± 2
Console Flow cfh:
Gas (1) 80
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ± 2
Voltage DC Operating 65 ± 2
Ampheres DC Operating 500 ± 2
Power Control Setting:
Start 0 ± Run 60% ±

COATING MATERIALS LIST

Batch or Lot No.
Manufacturer's ID Metco 106 NS

PART MATERIAL

Notes, Sketches, Etc.

POWDER FEEDER

Type Rotofeed Machine No. 2
Type of Carrier Gas Argon
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 8 ±
Spray Rate, lb/hr

Feed Worm Pitch
RPM 30 ± Speed Ind. ±
Vibrator on Off X Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'
Spray rate lb.hr. 3

COATING DATA

Powder Injection Port: No. 2
Front
Rear
Gun to Work Distance in. 4 ±
Part rpm 350 ± Sur.ft/min 91 ±
Coating Thickness:
As Sprayed .030
After Finishing .015
Preheat Temp
Spray Time (per cycle) 12 sec ±
Cool Time (per cycle) -- ±
Method of Cooling:
Air X Gas
Forced X Static
Coating Density

RESULTS OF TESTS

Cracked Adherence
Microexamination
NDT

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS plasma

SPRAYING SCHEDULE NO.

SPRAY IN ACCORDANCE WITH SPEC. NO.

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME BCL

SIGNATURE

DATE 2/11/75

PREPARATION

Method of Cleaning 200 P Alcohol
Masking Information
Grit Type Metco Lite
Grit Type and Size 60/40 Grit Blast psi 60
Nozzle to Work Distance 4-6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. 3M7A Gh
Nozzle (Cathode) Type No. 3M11A
Type of Gas Used (1) Argon
Type of Gas Used (2) Hydrogen
Nozzle Orifice Size .250

ARC GAS SETTINGS

Regulator (1) psi 100 ±
Regulator (2) psi 50 ±
Console psi 100/50 ±
Console Flow cfh:
Gas (1) 100
Gas (2) 50

POWER

Voltage DC Open Circuit 160 ±
Voltage DC Operating 60 ±
Ampheres DC Operating 400 ±
Power Control Setting:
Start 0 ± Run 50% ±

COATING MATERIALS LIST

Batch or Lot No.
Manufacturer's ID Metco 43C

PART MATERIAL

Notes, Sketches, Etc.

POWDER FEEDER

Type Rotofeed Machine No. 2
Type of Carrier Gas Argon
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 8 ±
Venturi Setting:
Flush Turns In Turns Out
Feed Worm Pitch
RPM 40 ± Speed Ind. ±
Vibrator on Off X Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'
Spray rate lb.hr 4

COATING DATA

Powder Injection Port: No. 2
Front
Rear
Gun to Work Distance in. 5 ±
Part rpm 350 ± Sur.ft/min 91 ±
Coating Thickness:
As Sprayed .030
After Finishing .015
Preheat Temp 150
Spray Time (per cycle) 12 sec ±
Cool Time (per cycle) -- ±
Method of Cooling:
Air X Gas
Forced X Static
Coating Density

RESULTS OF TESTS

Cracked Adherence
Microexamination
NDT

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS plasma

SPRAYING SCHEDULE NO. ______

SPRAY IN ACCORDANCE WITH SPEC. NO. ______

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME BCL

SIGNATURE ______

DATE 2/11/75

PREPARATION

Method of Cleaning 200 P alcohol
Masking Information ______
Grit Metco Lite
Grit Type and Size 60/40 Grit Blast psi 60
Nozzle to Work Distance 4 - 6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. 3M7A-GH
Nozzle (Cathode) Type No. 3M11A
Type of Gas Used (1) Argon
Type of Gas Used (2) Hydrogen
Nozzle Orifice Size .250

ARC GAS SETTINGS

Regulator (1) psi 100 ± 2
Regulator (2) psi 50 ± 2
Console psi 100/50 ± 2
Console Flow cfh:
Gas (1) 80
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ± 2
Voltage DC Operating 65 ± 2
Amperes DC Operating 500 ± 2
Power Control Setting:
Start 0 ± ______ Run 60% ± ______

COATING MATERIALS LIST

Batch or Lot No. ______
Manufacturer's ID Metco 63

PART MATERIAL

Notes, Sketches, Etc. ______

POWDER FEEDER

Type Rotofeed Machine No. 1
Type of Carrier Gas argon
Regulator psi 50 ± ______
Console psi 50 ± ______
Flow cm ______ ±CFH 8 ± ______
Spray Rate, lb/hr ______

Feed Worm Pitch ______
RPM 45 ± Speed Ind. ______ ± ______
Vibrator on ______ Off X Setting ± ______
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10 ft.
Spray rate lb. hr 3-1/2

COATING DATA

Powder Injection Port: No. 2
Front ______
Rear ______
Gun to Work Distance in. 5 ± ______
Part rpm 350 ± ______ Sur.ft/min 91 ± ______
Coating Thickness:
As Sprayed .030
After Finishing .015
Preheat Temp 150°F
Spray Time (per cycle) 12 sec ± ______
Cool Time (per cycle) -- ± ______
Method of Cooling:
Air X Gas ______
Forced X Static ______
Coating Density ______

RESULTS OF TESTS

Cracked Adherence ______
Microexamination ______
NDT ______

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS plasma

SPRAYING SCHEDULE NO. ____

SPRAY IN ACCORDANCE WITH SPEC. NO. ____

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME BCL

SIGNATURE ____

DATE 2/11/75

PREPARATION

Method of Cleaning 200 P alcohol
Masking Information ____
Grit Metcolite
Grit Type and Size 60/40 Grit Blast psi 60
Nozzle to Work Distance 4-6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. 3M7A-GH
Nozzle (Cathode) Type No. 3M11A
Type of Gas Used (1) Argon
Type of Gas Used (2) Hydrogen
Nozzle Orifice Size .250

ARC GAS SETTINGS

Regulator (1) psi 100 ± 2
Regulator (2) psi 50 ± 2
Console psi 100/50 ± 2
Console Flow cfh:
Gas (1) 80
Gas (2) 25

POWER

Voltage DC Open Circuit 160 ± 2
Voltage DC Operating 74 ± 2
Ampheres DC Operating 500 ± 2
Power Control Setting:
Start 0 ± ____ Run 67% ± ____

COATING MATERIALS LIST

Batch or Lot No. ____
Manufacturer's ID Metco 130

PART MATERIAL

Notes, Sketches, Etc. ____

POWDER FEEDER

Type Rotofeed Machine No. 1
Type of Carrier Gas Argon
Regulator psi 50 ± ____
Console psi 50 ± ____
Flow cm ____ ±CFH 8 ± ____
Spray Rate, lb/hr ____

Feed Worm Pitch ____
RPM 45 ± Speed Ind. ____ ± ____
Vibrator on ____ Off ____ Setting ____ ± ____
Feeder Hose to Gun:
Diameter I.D. .3/16 Length 10'
Spray rate lb.hr. 3

COATING DATA

Powder Injection Port: No 2
Front ____
Rear ____
Gun to Work Distance in. 5 ± ____
Part rpm 350 ± ____ Sur.ft/min 91 ± ____
Coating Thickness:
As Sprayed .030
After Finishing .015
Preheat Temp 150
Spray Time (per cycle) 12 sec ± ____
Cool Time (per cycle) --- ± ____
Method of Cooling:
Air X Gas ____
Forced X Static ____
Coating Density ____

RESULTS OF TESTS

Cracked Adherence ____
Microexamination ____
NDT ____

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS plasma

SPRAYING SCHEDULE NO.

SPRAY IN ACCORDANCE WITH SPEC. NO.

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME BCL

SIGNATURE

DATE 2/11/75

PREPARATION

Method of Cleaning 200 P alcohol
Masking Information
Grit Metco Lite
Grit Type and Size 60/40 Grit Blast psi 60
Nozzle to Work Distance 4-6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. 3M7A-GH
Nozzle (Cathode) Type No. 3M11A
Type of Gas Used (1) Argon
Type of Gas Used (2) Hydrogen
Nozzle Orifice Size .250

ARC GAS SETTINGS

Regulator (1) psi 100 ± 2
Regulator (2) psi 50 ± 2
Console psi 100/50 ± 2
Console Flow cfh:
Gas (1) 80
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ± 2
Voltage DC Operating 65 ± 2
Ampheres DC Operating 500 ± 2
Power Control Setting:
Start 0 ± Run 60 ±

COATING MATERIALS LIST

Batch or Lot No.
Manufacturer's ID Metco 450

PART MATERIAL

Notes, Sketches, Etc.

POWDER FEEDER

Type Rotofeed Machine No. 1
Type of Carrier Gas Argon
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 8 ±
Spray Rate, lb/hr

Feed Worm Pitch
RPM 40 ± Speed Ind. ±
Vibrator on Off X Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'
Spray rate lb hr 4

COATING DATA

Powder Injection Port: No. 2
Front
Rear
Gun to Work Distance in. 5 ±
Part rpm 350 ± Sur.ft/min 91 ±
Coating Thickness:
As Sprayed .030
After Finishing .015
Preheat Temp 150
Spray Time (per cycle) 12 sec ±
Cool Time (per cycle) --- ±
Method of Cooling:
Air X Gas
Forced X Static
Coating Density

RESULTS OF TESTS

Cracked Adherence
Microexamination
NDT

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS Plasma

SPRAYING SCHEDULE NO. ____

SPRAY IN ACCORDANCE WITH SPEC. NO. ____

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME NOSL

SIGNATURE ____

DATE ____

PREPARATION

Method of Cleaning degrease
Masking Information ____
Grit Type Metcolite
Grit Size C Grit Blast psi 80
Nozzle to Work Distance 4 - 6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. G
Nozzle (Cathode) Type No. 11A
Type of Gas Used (1) N_2
Type of Gas Used (2) H_2
Nozzle Orifice Size --

ARC GAS SETTINGS

Regulator (1) psi 50 ±
Regulator (2) psi 50 ±
Console psi 50 ±
Console Flow cfh:
Gas (1) 100
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ±
Voltage DC Operating 72 ±
Ampheres DC Operating 400 ±
Power Control Setting:
Start 0 ± Run 61 ±

COATING MATERIALS LIST

Batch or Lot No. ____
Manufacturer's ID Metco 63NS

PART MATERIAL

Notes, Sketches, Etc. ____

POWDER FEEDER

Type 3MP Machine No. ____
Type of Carrier Gas N_2
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 37 ±
Venturi Setting:
Flush ____ Turns In ____ Turns Out ____
Feed Worm Pitch S
RPM 15 ± Speed Ind. ____ ±
Vibrator on ____ Off ____ Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'
Spray Rate lb/hr 6

COATING DATA

Powder Injection Port: No. 1
Front ____
Rear ____
Gun to Work Distance in. 5 ±
Part rpm 350 ± Sur.ft/min ±
Coating Thickness:
As Sprayed .022
After Finishing .015
Preheat Temp 120 F
Spray Time (per cycle) 10 sec ±
Cool Time (per cycle) -- ±
Method of Cooling:
Air ✓ Gas ____
Forced ✓ Static ____
Coating Density ____

RESULTS OF TESTS

Cracked Adherence ____
Microexamination ____
NDT ____

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS Plasma

SPRAYING SCHEDULE NO.

SPRAY IN ACCORDANCE WITH SPEC. NO.

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME NOSL

SIGNATURE

DATE

PREPARATION

Method of Cleaning degrease
Masking Information
Grit Metcolite
Grit Size C Grit Blast psi 80
Nozzle to Work Distance 4 - 6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. G
Nozzle (Cathode) Type No. 11A
Type of Gas Used (1) N_2
Type of Gas Used (2) H_2
Nozzle Orifice Size --

ARC GAS SETTINGS

Regulator (1) psi 50 ±
Regulator (2) psi 50 ±
Console psi 50 ±
Console Flow cfh:
Gas (1) 100
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ±
Voltage DC Operating 74 ±
Ampheres DC Operating 400 ±
Power Control Setting:
Start 0 ± Run 60 ±

COATING MATERIALS LIST

Batch or Lot No.
Manufacturer's ID Metco 43 C

PART MATERIAL

Notes, Sketches, Etc.

POWDER FEEDER

Type 3MP Machine No.
Type of Carrier Gas N_2
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 37 ± - - -
Spray Rate, lb/hr 5
Flush Turns In Turns Out
Feed Worm Pitch
RPM 45 ± Speed Ind. ±
Vibrator on Off Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'

COATING DATA

Powder Injection Port: No. 1
Front
Rear
Gun to Work Distance in. 6 ±
Part rpm 350 ± Sur.ft/min ±
Coating Thickness:
As Sprayed .022
After Finishing .015
Preheat Temp 120 F
Spray Time (per cycle) 10 sec ±
Cool Time (per cycle) --- ±
Method of Cooling:
Air ✓ Gas
Forced ✓ Static
Coating Density

RESULTS OF TESTS

Cracked Adherence
Microexamination
NDT

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS Plasma

SPRAYING SCHEDULE NO.

SPRAY IN ACCORDANCE WITH SPEC. NO.

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME NOSL

SIGNATURE

DATE

PREPARATION

Method of Cleaning degrease
Masking Information
Grit Metcolite
Grit Size C Grit Blast psi 80
Nozzle to Work Distance 4 - 6 "

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. G
Nozzle (Cathode) Type No. 11A
Type of Gas Used (1) N_2
Type of Gas Used (2) H_2
Nozzle Orifice Size

ARC GAS SETTINGS

Regulator (1) psi 50 ±
Regulator (2) psi 50 ±
Console psi 50 ±
Console Flow cfh:
Gas (1) 75
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ±
Voltage DC Operating 76 ±
Ampheres DC Operating 500 ±
Power Control Setting:
Start 0 ± Run 70 ±

COATING MATERIALS LIST

Batch or Lot No.
Manufacturer's ID Metco 106NS

PART MATERIAL

Notes, Sketches, Etc.

POWDER FEEDER

Type 3MP Machine No.
Type of Carrier Gas N_2
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 37 - - ± - - -
Spray Rate, lb/hr - 5
Flush Turns In Turns Out
Feed Worm Pitch S
RPM 45 ± Speed Ind. ±
Vibrator on Off Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'

COATING DATA

Powder Injection Port: No. 2
Front
Rear
Gun to Work Distance in. 4 ±
Part rpm 350 ± Sur.ft/min ±
Coating Thickness:
As Sprayed .022
After Finishing .015
Preheat Temp 120
Spray Time (per cycle) 10 sec ±
Cool Time (per cycle) -- ±
Method of Cooling:
Air ✓ Gas
Forced ✓ Static
Coating Density

RESULTS OF TESTS

Cracked Adherence
Microexamination
NDT

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS Plasma

SPRAYING SCHEDULE NO.

SPRAY IN ACCORDANCE WITH SPEC. NO.

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME NOSL

SIGNATURE

DATE

PREPARATION

Method of Cleaning Degrease
Masking Information
Grit Metcolote
Grit Size C Grit Blast psi 80
Nozzle to Work Distance 4 - 6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. G
Nozzle (Cathode) Type No. 11A
Type of Gas Used (1) N_2
Type of Gas Used (2) H_2
Nozzle Orifice Size

ARC GAS SETTINGS

Regulator (1) psi 50 ±
Regulator (2) psi 50 ±
Console psi 50 ±
Console Flow cfh:
Gas (1) 75
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ±
Voltage DC Operating 76 ±
Ampheres DC Operating 500 ±
Power Control Setting:
Start 0 ± Run 71 ±

COATING MATERIALS LIST

Batch or Lot No.
Manufacturer's ID Metco 130

PART MATERIAL

Notes, Sketches, Etc.

POWDER FEEDER

Type 3MP Machine No.
Type of Carrier Gas N_2
Regulator psi 50 ±
Console psi 50 ±
Flow cm ±CFH 37 --- ± ---
Spray Rate, lb/hr 3

Feed Worm Pitch S
RPM 24 ± Speed Ind. ±
Vibrator on Off Setting ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10

COATING DATA

Powder Injection Port: No. 2
Front
Rear
Gun to Work Distance in. 5 ±
Part rpm 350 ± Sur.ft/min ±
Coating Thickness:
As Sprayed .022
After Finishing .015
Preheat Temp 120
Spray Time (per cycle) 10 sec ±
Cool Time (per cycle) -- ±
Method of Cooling:
Air ✓ Gas
Forced ✓ Static
Coating Density

RESULTS OF TESTS

Cracked Adherence
Microexamination
NDT

PLASMA-SPRAY PARAMETER SHEET

SPRAYING PROCESS Plasma

SPRAYING SCHEDULE NO. ____

SPRAY IN ACCORDANCE WITH SPEC. NO. ____

GUN TYPE Metco Gun Model No. 3MB

SPRAY FACILITY NAME NOSL

SIGNATURE ____

DATE ____

PREPARATION

Method of Cleaning degrease
Masking Information ____
Fixturing Type Metcolite
Grit Size C Grit Blast psi 80
Nozzle to Work Distance 4 - 6"

SPRAY-EQUIPMENT SUPPLEMENT

Nozzle (Anode) Type No. G
Nozzle (Cathode) Type No. 11A
Type of Gas Used (1) N_2
Type of Gas Used (2) H_2
Nozzle Orifice Size --

ARC GAS SETTINGS

Regulator (1) psi 50 ±
Regulator (2) psi 50 ±
Console psi 50 ±
Console Flow cfh:
Gas (1) 80
Gas (2) 15

POWER

Voltage DC Open Circuit 160 ±
Voltage DC Operating 65 ±
Ampheres DC Operating 500 ±
Power Control Setting:
Start 0 ± Run 50 ±

COATING MATERIALS LIST

Batch or Lot No. ____
Manufacturer's ID Metco 450

PART MATERIAL

Notes, Sketches, Etc. ____

POWDER FEEDER

Type 3MP Machine No. ____
Type of Carrier Gas N_2
Regulator psi 50 ±
Console psi 50 ±
Flow cm ____ ±CFH 37 ±
Spray Rate, lb/hr 5
Flush ____ Turns In ____ Turns Out ____
Feed Worm Pitch ____
RPM 15 ± Speed Ind. ____ ±
Vibrator on ____ Off ____ Setting ____ ±
Feeder Hose to Gun:
Diameter I.D. 3/16 Length 10'

COATING DATA

Powder Injection Port: No. 2
Front ____
Rear ____
Gun to Work Distance in. 5 ±
Part rpm 350 ± Sur.ft/min ____ ±
Coating Thickness:
As Sprayed .022
After Finishing .015
Preheat Temp 120
Spray Time (per cycle) 10 sec ±
Cool Time (per cycle) -- ±
Method of Cooling:
Air ✓ Gas ____
Forced ✓ Static ____
Coating Density ____

RESULTS OF TESTS

Cracked Adherence ____
Microexamination ____
NDT ____

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Plasma Spraying, Plasma, Metal Spraying, Life Cycle Testing, Leak Testing, Plasma Powder Sealers, Salt Corrosion Tests, Seal Performance, Friction of Metal Sprayed Parts, Wear of Metal Sprayed Parts

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program was conducted for the purpose of providing reference data on plasma-sprayed coatings for use in the design and repair/salvage of naval ordnance hardware. Plasma-spray deposition parameters and surface finishing techniques were developed for metal and ceramic plasma-sprayed coatings applied to mild steel, stainless steel, aluminum, brass, and K-monel. The wear characteristics of the coated shafts versus a variety of bushing materials were

(Cont'd)

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studied in hydraulic piston wear tests during which oil leakage rates as a function of surface finish were determined using Teflon and urethane seal materials.

As a result of the program, plasma-sprayed coatings and bushing material were identified that provided friction and wear performance at least comparable to that provided by baseline conventional cylinder materials. Teflon seals were found to provide the most reliable dynamic seal performance, and a low viscosity, polyester type resin sealer (Loctite 290) was found to be an effective sealant for both hydraulic and pneumatic applications.

The plasma-spray parameters and processing parameters and techniques developed in this program and information on the coating properties and process limitations derived from this work will be incorporated in the plasma-spray handbook being prepared for NOSL under Contract No. N-00197-73-C-0430.(U).